LIMITED CIRCULATION

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Agricultural Memorandum No 1023

The Effect of Aspect Upon the Temperature of the Ground and Associated Changes in Accumulated Temperature

by M. J. Lee

SUMMARY

Calculations based on theory and observations have been made to assess the effect of aspect upon the maximum temperature attained by the ground during the day. The heat input and hence the temperature rise depends upon the angle of incidence of the sun's rays on the surface; the smaller the angle, the greater the heating. Altering the orientation of the ground surface will change the angle of incidence, and lead to variations in the maximum surface temperature, all other things being equal. Differences in mean daily temperature can vary by a few degrees between horizontal and north or south facing slopes in the Spring. In Summer and Winter the effect of inclination is not so great.

An important factor in determining the agricultural capability of land is the January-June Accumulated Mean Daily Temperature which could be affected quite considerably by the orientation of the land. However the height above the ground at which the temperature measurements are made is critical, since the effect on atmospheric temperature of heteorogeneous ground heating rapidly decreases with height.

1. Introduction

As part of the Land Classification Project there was a need for a nationwide map of Potential Soil Moisture Deficit (PSMD), for which a knowledge of Potential Evaporation (PE) was required. Studies by Field (1983a) have shown that it is impossible to map PE objectively using the data currently available. However, at locations where PSMD could be accurately calculated Keers (1983) has found that a good relationship exists between PSMD, January-June accumulated rainfall and January-June accumulated temperature (the sum of the average of the daily maximum and minimum). Accumulated temperature can be mapped across the country since temperature is measured at many locations, and its variation with altitude (the Lapse Rate) is well known. An attempt has been made to determine whether the aspect of the land will further modify the accumulated temperature: for example, how much warmer are south facing slopes than north facing slopes?

There has been much investigation into the variation of short wave radiation intensity on slopes of different orientations at different times of the day and year. (See for example Thompson and Barrie (1978), Smith (1972), Gadd and Keers (1970)). In contrast, very little work has been done to convert the radiation measurements into temperatures, either on the

ground or in the atmosphere immediately above. Most of the research into radiation/temperature relationships has been carried out in the Soviet Union. M . P. Chizhevskaya (1960) made some measurements on grassy slopes of sandy loan near Leningrad, and from these obtained a good correlation between ground temperature and the net radiation balance. In the absence of any other guidance, the relationships so derived have been used in this study.

2. Method

The following steps were taken to produce the corrections for slope and aspect that need to be made to January-June accumulated temperatures.

i) Calculate the position of the sun for each hour of daylight in the middle of each month.

ii) Calculate the total direct short wave radiation on a flat surface at midday and on the inclined surfaces for each hour.

iii) Calculate the net radiation by taking account of long wave and diffuse radiation and albedo.

iv) Calculate the time of maximum insolation and hence of maximum ground temperature for the sloping surfaces.

v) Convert the net radiation to temperature by an empirical equation.

vi) Calculate daily mean temperature using the average monthly grass minimum and the calculated maximum.

vii) Add up the differences in mean daily temperature for flat and sloping surfaces from January-June.

3. Theory

3.1 Solar Angle - The intensity of solar radiation on a plane, ignoring atmospheric attenuation is given by

$$I_p = I_o \cos\beta \qquad (1)$$

where I_o = Solar Constant = $1360 \times (1 + 0.035 \times \cos(d \times 360/365))$ Wm^{-2}
β = Angle between the sun and the perpendicular to the plane (ie the Angle of Incidence).
d = day of year.

From Robinson (1966)

$$\cos\beta = \cos\epsilon(\sin\phi\sin\delta+\cos\phi\cos\delta\cos\tau)+\sin\epsilon\{\cos A(\tan\phi (\sin\phi\sin\delta+\cos\phi\cos\delta\cos\tau)-\sin\delta\sec\phi)+\sin A\cos\delta\sin\tau] \qquad (2)$$

Where ϵ = slope of plane
A = Azimuth of normal to the plane (south=0°, north =±180°, east=-90° west=90°)
δ = Declination of sun = $23.5 \cos\{(d-173)/365\}$
d = day of year

ϕ = latitude (degrees)
τ = hour angle = (t-12) x 360/24
t = time in hours from local midnight.

3.2 Total Radiation - From equation (1), the total radiation incident on the surface over any period of time within a day is

$$I_o \int_{t_1}^{t_2} \cos\beta \, dt$$

Using equation (2)

$$\int_{t_1}^{t_2} \cos\beta \, dt = (\sin\delta(\sin\phi(\cos\epsilon+\sin\epsilon\cos A\tan\phi)-\sin\epsilon\cos A\sec\delta))\,(t_2-t_1) + (\cos\delta\cos\phi(\cos\epsilon+\sin\epsilon\cos A\tan\phi))\,{}^{12}/_{\pi}\,(\sin\tau_2 - \sin\tau_1) - (\sin\epsilon\sin A\cos\delta)\,{}^{12}/_{\pi}\,(\cos\tau_2 - \cos\tau_1) \quad (3)$$

For a horizontal surface (ϵ=A=0) equation (3) can be considerably simplified to

$$\int_{t_1}^{t_2} \cos\beta \, dt = \sin\phi\sin\delta(t_2-t_1)+(\cos\phi\cos\delta\,{}^{12}/_{\pi}\,(\sin\tau_2-\sin\tau_1)) \quad (4)$$

3.3 Net Radiation - It is the strength of the direct solar radiation which displays most variability with changes in the attitude of the ground, but diffuse sky radiation also alters by a small amount. Account must also be taken of atmospheric attenuation and surface albedo. From Gadd and Keers (1970) the following equation was used to describe the net radiation falling onto the surface in terms of direct solar radiation.

$$R_n = \left[\frac{1-\alpha}{1+\gamma}\right] Ip\,F\cos\beta - I_o \quad (5)$$

Where F = Atmospheric Transmission Function = 0.6 + 0.2 $\cos\beta$
α = Surface albedo (0.25)
γ = Heating coefficient (0.1)
I_o = Long wave radiation to space = $0.05I_o$

Equation (5) is integrated with respect to time to get the total net radiation over a time period. For simplicity F was taken to be independent of time, making $\cos\beta$ the only time dependent term in equation (5). The integration of $\cos\beta$ is shown in equation (4). Ip F$\cos\beta$ includes a diffuse radiation element for a flat surface. From ASHRAE (1981) the diffuse radiation on a sloping surface is given as

$$I_d = Ip\,C(1+\cos\epsilon)/2 \quad (6)$$

Where C is a function of the time of year, ranging from 0.06 in January to 0.14 in July. To establish the change in the net radiation due to the diffuse component for a sloping surface, I_d for a horizontal surface (ϵ=0) is subtracted from R_n and the sloping surface value added on. The change in net radiation caused by correcting the diffuse radiation for slope amounted to only a few percent.

3.4 Corrections for cloud - In overcast conditions direct solar radiation is cut off from the surface, leaving only the diffuse short wave component. Since diffuse radiation is almost independent of direction, in overcast weather all slopes will heat up at approximately the same rate. The longwave component is also modified, because in cloudy weather about 80% of the longwave radiation emitted by the surface is being emitted back towards the earth by cloud.

The correction for short wave radiation which is made to the Ip Fcosβ term in equation (5) is derived from Thompson et al (1981).

$$I_p' = I_p \times (0.25 + 0.53\ {}^{n}/_{N})$$

Where Ip' = Short wave radiation corrected for average monthly cloud cover
n = Average daily sunshine over a month
N = Average day length over a month

The values of n and N were derived from climatological records for central England.

The long wave radiation correction to the Lo term of equation (5) is again derived by Thompson et al (1981) as

$$L_o' = L_o \times (0.2 + 0.8\ {}^{n}/_{N})$$

3.5 Time of Maximum Temperature - According to Chizhevskaya (1960) maximum surface temperature will occur at maximum insolation. The time of maximum insolation depends upon the orientation of the slope, but is always at midday for a flat surface. For sloping surfaces, each hour the sun is above the horizon the net radiation is calculated until the maximum insolation is reached. For north facing slopes, the maximum could occur soon after sunrise, or just before sunset.

3.6 The Maximum Temperature - Figure 1 shows the linear relationship derived by Chizhevskaya (1960) between net radiation and surface temperature. There are two relationships, one for use before 1300Z and the other for use after 1300Z. In the afternoon, all other things being equal, higher surface temperatures are attained than in the morning for the same radiation intensity. This apparent anomaly arises because most west facing slopes benefit from a morning of solar and conductive heating before the maximum insolation is reached, which the eastern slopes do not have. The direction of slope apparently has no effect on the temperature/radiation relationship.

The temperature of east facing slopes remains around the maximum for most of the afternoon, whereas west facing slopes have a more distinct peak. The daily temperature profiles for east and west facing slopes are shown schematically in figure 2.

3.7 Accumulated Temperature - The accumulated temperature is the sum of the daily average temperatures. The daily average temperature is the average of the minimum and maximum temperature, with slight modifications for negative temperatures (see Field (1983b)). Chizhevskaya shows that aspect does not affect the night minimum temperature, and therefore all slopes can be assumed to have virtually the same minimum temperatures, all other things being equal. It is solely the radiation effects altering the maximum temperature which change the accumulated temperature when ground orientation changes.

4. Generalizations

In an exercise of this sort it is impossible to allow for all situations, averages and generalizations must be resorted to. All calculations have been made for 52°N and carried out on the 15th of the month. Temperatures were calculated for slopes at every 45° of azimuth and inclined at 5° intervals between 5° and 45°.

Average grass minimum temperatures at Elmdon were used, and are as follows.

MONTH	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE
Grass Minimum	-1.0	-1.0	0.0	2.0	4.0	8.0

The results presented are therefore broadly representative of England and Wales as a whole. If the need arose, however, specific locations could be studied.

5. Results

The corrections (in degree-days) for slope and aspect that should be made to January to June accumulated temperatures are shown in Table 1. Accumulated temperatures over this period for flat surfaces would be in the range 1400-1600 degree days for most of England and Wales. And so for surfaces tilting north at large angles a change of up to 50% would be expected. For south facing slopes the effect on accumulated temperature is not so great, with increases of up to 25%.

A slope of any pitch facing to the north of north west or north east will over the six months have a lower temperature than a flat surface. Shallow pitched east and west facing slopes will also be cooler, but by less than 3%, whilst for all other aspects temperature is increased. The ground that would be warmest over the six months faces between south and west at 45°, although that would not be the best inclination on each individual month. The morning pre-heating effect on west facing slopes is evident as an asymetry in the accumulated temperature differences between east and west facing slopes.

Table 1 Corrections to January - June Accumulated Temperature for Slope and Aspect
Units: Degree days.

Aspect (Direction Surface is facing)

Slope in Degrees

	NORTH	NORTH-EAST	EAST	SOUTH-EAST	SOUTH	SOUTH-WEST	WEST	NORTH-WEST
5°	-145	-110	-40	25	41	25	-40	-110
10°	-245	-175	-35	90	120	90	-30	-175
15°	-340	-225	-10	140	190	140	0	-220
20°	-440	-275	10	200	250	200	30	-260
25°	-535	-310	40	250	300	260	85	-275
30°	-640	-325	65	285	335	300	125	-270
35°	-725	-330	100	310	355	335	185	-245
40°	-760	-325	130	325	365	355	240	-200
45°	-725	-310	145	335	365	370	285	-135

6. Restrictions

It must be emphasized that the results described here apply to a particular type of soil and vegetation, and are made as general as possible for the whole of England and Wales. It should be noted that the radiation/ temperature relationship that has been used was derived in a country of very different climate.

Soil moisture and its associated latent heat transfers will be a major factor in determining the pattern of temperature changes. Dry soils will heat up faster than wet soils. In the absence of wind sloping ground would receive less rain than flat ground in proportion to the cosine of the angle of slope. However the presence of wind during rainfall is likely to cause east facing slopes to receive least rain. They will therefore be driest and heat up most, on average, but local climate and geography will create wide variations about this norm.

The complexity of this soil moisture problem precludes it from examination in this study, although its possible effects must not be underestimated.

7. Air Temperatures

Air temperature changes approximately logarithmically with height above the effective crop height, and is scaled by the roughness length of the vegetation. Therefore, for bare soil and short vegetation, which have low effective heights and short roughness lengths, at the height of a screen (1.2m) variations in ground temperature have been virtually removed from the adjacent air. Chizhevskaya reached the same conclusion experimentally with differences between north and south slopes of less than 1°C, even in still air conditions.

For tall vegetation, such as corn, the higher effective height and increased roughness would cause heteorogeneous ground heating to be reflected in air temperatures somewhat more obviously.

All references to accumulated temperatures in the Land Classification Project have thus far related to mean daily air temperature. It therefore follows that over short vegetation and bare soil, aspect would not significantly affect accumulated temperature, but over mature crops there would be a marked affect. However, since it is the temperatures a few centimetres above and below the ground surface that determine the type and productivity of crops grown, it is probably more realistic to adjust the accumulated temperature by the quantities derived in this exercise.

Day to day changes in air temperature between slopes of different aspect in the same geographical location do occur, but these changes are advectively induced. The temperature differences depend on wind speed, wind direction and the general synoptic conditions, and will therefore in time and in most locations cancel out.

8. Implications for Land Classification

As a general rule, all other things being equal, a change of about 150 degree days in accumulated temperature over the reference period, corresponds to 1 class change in the Land Classification, although for a

change from good quality Class 1 land to Class 2 a change of up to 400 degree days may be necessary (see Bibby et al 1982). From Table 1, Table 2 has been derived, indicating the deviation in slope from horizontal needed to change the land class for various aspects.

TABLE 2 - Slope of land (in degrees) needed for changes in the land class to occur.

	NUMBER OF CLASS CHANGES							
ASPECT	+2	+1	0	-1	-2	-3	-4	-5
NORTH	-	-	0-1	2-8	9-17	18-24	25-32	33-45
NORTH EAST	-	-	0-2	3-15	16-45	-	-	-
EAST	-	32-45	0-31	-	-	-	-	-
SOUTH EAST	23-45	8-22	0-7	-	-	-	-	-
SOUTH	19-45	7-18	0-6	-	-	-	-	-
SOUTH WEST	23-45	8-22	0-7	-	-	-	-	-
WEST	39-45	24-38	0-23	-	-	-	-	-
NORTH WEST	-	-	0-2	3-16 38-45	17-37	-	-	-

Changes in soil wetness, crop type and surrounding topography will all act to modify the categories above. Of these, topography is invariant from year to year, and consequently is the most simple to take account of. Very special care should be taken when applying these results to valleys where delayed sunrise and early sunset, with periodic shading within the day, will reduce aspect effects on south facing slopes and enhance them on north facing slopes.

9. Conclusion

Significant changes in maximum ground surface temperature can result from altering the slope and aspect, whilst keeping all other contributing variables constant. Minimum temperatures are however, virtually unaffected, as indeed are air maximum temperatures at screen height. Therefore over short vegetation changes in accumulated temperature with aspect would be minimal on the whole, although the larger the scale of topography then the more possibility there is of the temperature of stagnant air becoming constrained by the temperature of the underlying surface. This would apply mostly to sheltered north facing hillsides. As the height of the vegetation increases the 'surface' and screen temperatures become more closely coupled.

The changes in accumulated temperature described in this paper could therefore be considered as maximum values, and depending upon the height at which the temperature is considered to be most important, could be reduced accordingly.

References

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Any comments or suggestions on this paper should be referred to the author.

Met O 8a
Meteorological Office
London Road
Bracknell
Berks RG12 2SZ

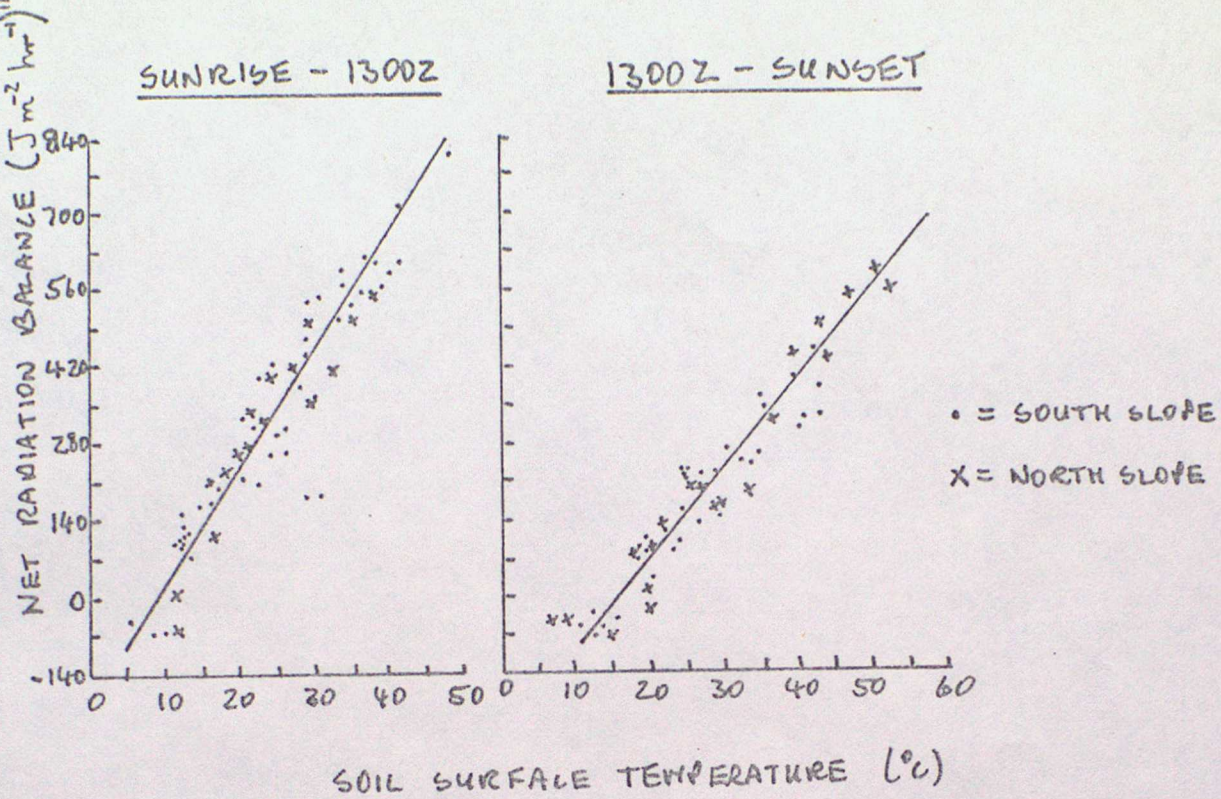
May 1984

Figure Legends

Figure 1. Graphs showing the relationship between soil surface temperature and radiation balance.
a) From sunrise to 1300Z
b) From 1300Z to sunset.

Figure 2. A graph showing schematically the way in which surface temperature changes with time of day on east and west facing slopes, on a typical cloudless summer day.

FIGURE 1

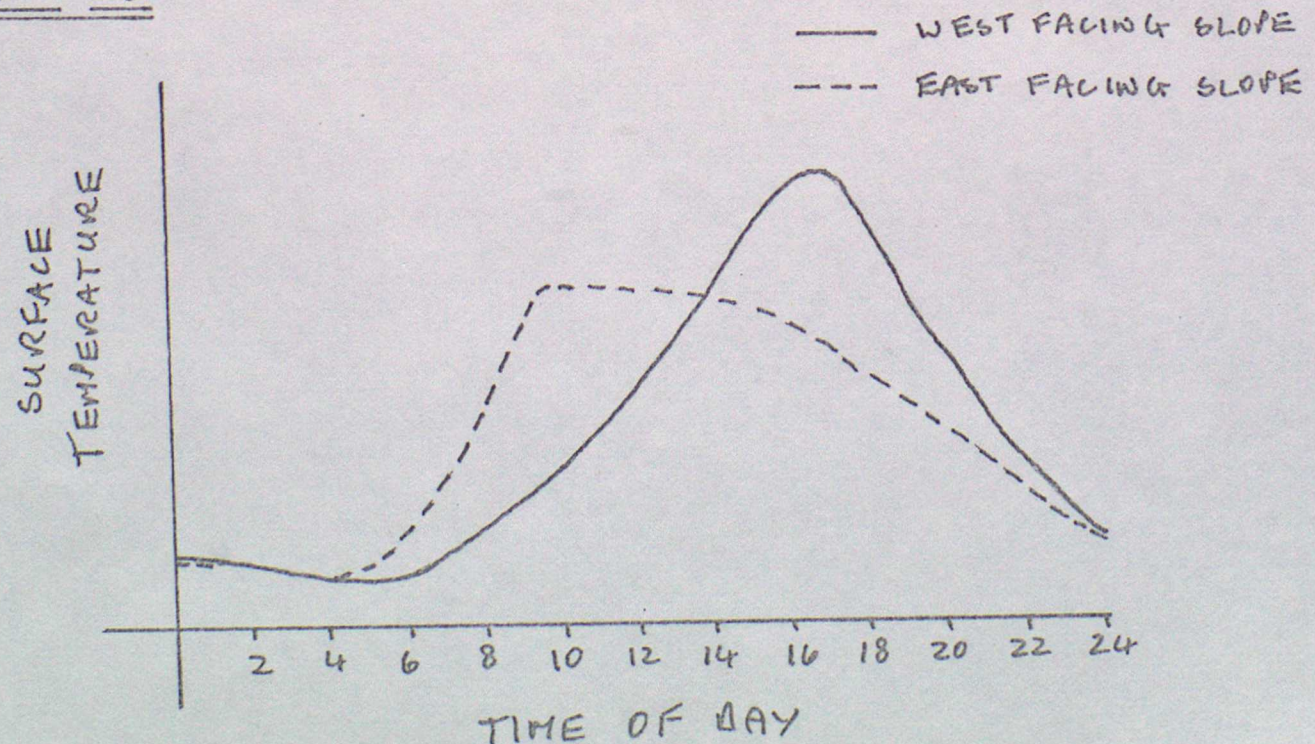


SUNRISE - 1300Z: — $TEMP = T_{MIN} + 0.0478 * RADIATION$

1300Z - SUNSET: — $TEMP = CON + 0.0633 * RADIATION$

$CON = T_{1300Z} - 0.0633 * RADIATION_{1300Z}$

FIGURE 2



APPENDIX 1 Computing Details

The JCL required to run the program to extract the accumulated temperature corrections is as follows:-

```
// EXEC FORTVLG
//LKED.OBJ DD DSN=MO8.OBJLIB,DISP=SHR
//LKED.MET DD DSN=MET.PROGLIB,DISP=SHR
//LKED.SYSIN DD *
         INCLUDE OBJ(USLOPE)
         INCLUDE MET(MOVECH)
//GO.SYSIN DD *
     DATA
//
```

The data can be inserted in any format that suits the user. The data are as follows:-

First month; last month
Most southerly latitude; Most northerly latitude; latitude increment
(All in tenths of degrees)
Least slope; greatest slope; slope increment (in degrees)
Azimuth limits (north = $\pm$180°, south = 0°, west slopes +ve and east slopes -ve), Azimuth increment (in degrees).

In an average run the program will use less than 3 Units. The program is available for inspection on MO8.SRCELIB as USLOPE, and the JCL can be found on MO8.JCLLIB.